

TITLE OF THE INVENTION

Thin-Layer Porous Optical Sensors for Gases and Other Fluids

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims benefit of U.S. Provisional Patent Application, Serial Number 60/533,570, entitled "Thin-Layer Porous Optical Interferometric Sensors for Gases and Other Fluids," filed December 31, 2003.

STATEMENT OF FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

[0002] Research described in this application was sponsored by the Human Effectiveness Directorate, Air Force Research Laboratory, Air Force Materiel Command, United States Air Force, under grant number F33615-00-2-6059.

FIELD OF THE INVENTION

[0003] The present invention relates to a thin layer electrode and methodologies for taking spectroscopic or interferometric measurements of a fluid. In particular, the presently disclosed technology relates to an optically reflective thin layer electrode (ORTLE) for, e.g., spectroscopic interrogation of a solution phase within channels or pores of a film in the ORTLE.

BACKGROUND OF THE INVENTION

[0004] Since first reported in 1967, optically transparent thin layer electrodes (OTTLEs) have been used for thin layer studies. Spectroelectrochemistry, for example, is a combination of electrochemical and spectroscopic techniques in which optical measurements are referred to the potential of a working electrode. Thin-layer spectroelectrochemistry is possibly the simplest type of spectroelectrochemistry and has advantages such as rapid and exhaustive electrolysis and small volume features. A typical application of an OTTLE is the spectroscopic study of "redox" processes; i.e.,

reactions in which the acceptance of an electron (reduction) by a material is matched with the donation of an electron (oxidation). Various spectroscopic techniques such as luminescence spectroscopy, Fourier transform infrared (FTIR) difference spectroscopy and ultraviolet/visible/near infrared (UV/vis/NIR) have been coupled with electrochemical techniques via OTTLEs. A variety of OTTLE designs for many purposes have been developed, and all generally operate on transmittance principles.

BRIEF SUMMARY OF THE INVENTION

[0005] The present invention is directed to spectroelectrochemical, spectroscopic and/or interferometric analyses of a material trapped in pores of a thin layer film. More specifically, the invention is directed to an optically reflective thin layer electrode (ORTLE) that operates on reflectance principles; i.e., the ORTLE collects reflectance rather than facilitating transmittance through a fluid. As used herein, the term fluid is used to mean a continuous amorphous medium, matter or substance – e.g., a liquid, including a solution, or a gas - that tends to flow and to conform to an outline of its container and will not destroy the thin layer film.

[0006] The ORTLE is fabricated, for instance, by anodizing a thin layer of aluminum sputtered onto a glass substrate, such as a float glass microscope slide, to create a 250 nm to 1000 nm-thick, porous, aluminum oxide (alumina) film. The resulting alumina film is transparent and contains channels or pores that vary from approximately 80 to 100 nm in diameter with depths of approximately 250 nm to 1000 nm. The thickness of the alumina film – and thus the depth of the pores – can be altered by controlling the thickness of the original aluminum film. Although alumina is provided by way of an enabling example, any porous membrane with channels or pores to trap the fluid for spectroscopic, interferometric, or spectroelectrochemical measurements can be used to practice the invention.

[0007] In one aspect of the invention, a thin film of gold is sputtered atop the alumina film. The gold layer adheres to surface points of the alumina film such that the gold layer remains porous to allow a solution into the pores of the alumina film while remaining optically thick and reflective. The gold layer is filled with holes each having a diameter substantially less than the

wavelength of visible light. As discussed below, the gold layer can serve as an electrode but is not limited to such use. Furthermore, other metals and materials with reflective properties can be substituted for gold and thus used to practice the invention.

[0008] As described in detail herein, the ORTLE interrogates a very thin film sample based on porous alumina. Through the use of a combination of specular reflectance spectroscopy and chronoamperometry, the spectroelectrochemical study is confined to that solution contained within the pores of the ORTLE. Specifically, spectroscopy interrogates a solution phase within the pores of the alumina film between the electrode face and a window behind it. Reflectance measurements are thus made through the glass slide but do not interrogate a surrounding bulk solution.

[0009] According to exemplary experiments described herein, the reflectance measurements show spectral features that shift with the optical properties of the material filling the pores of the alumina film. The stability of the ORTLE spectrum and its origin are described by examples below to show how an applied potential affects the observed spectrum in a simple solution. For instance, a series of experiments in which the potential of the ORTLE is stepped negatively to various values in an aqueous sodium sulfate solution shows that interference fringes shift measurably in the ORTLE spectrum at potentials several hundred millivolts positive of the potential at which gas evolution was visible to the naked eye.

[0010] According to a particular aspect of the invention, a method is provided for analyzing matter such as by interferometric, spectroscopic, and/or electrochemical and optical spectroscopic (spectroelectrochemistry) techniques. The method includes the steps of (a) introducing a liquid or gaseous matter into an optically reflective thin layer electrode, the electrode including a transparent base substrate with alumina film disposed thereon, the alumina film defining a plurality of pores therein, and a gold film disposed on the alumina film such that a quantity of the liquid or gaseous matter can enter at least one of the pores; (b) applying a potential to the gold film such that the quantity of the liquid or gaseous matter in the pores is isolated from a remaining bulk of the liquid or gaseous matter disposed about the electrode; and (c) directing light from a source into the electrode from proximate the

base substrate in a direction of the gold film, the fold film under the potential configured to reflect the light into the quantity of the liquid or gaseous matter in the pores for analysis of the reflected light.

[0011] According to the method, the liquid or gaseous matter is selected from the group consisting of potassium ferricyanide, sodium sulfate, water and solutions thereof. The liquid or gaseous matter can be a solution of 0.01M ferricyanide, 0.05M sodium sulfate, and deionized water. The transparent base substrate is made of glass. The applied potential is between +0.4V to -1.5V and can be held for between about 200 seconds to about 400 seconds.

[0012] According to the method, the light can be directed at the base substrate at about a 45° angle, and may further include the step of monitoring the reflected light in the quantity of the liquid or gaseous matter isolated in the pores by reflectance spectroscopy.

[0013] According to another aspect of the invention, an optically reflective thin layer includes a transparent base substrate; a film disposed on the base substrate, the film defining a plurality of pores therein; and a reflective material disposed on the film such that the pores are exposed to atmosphere, the reflective material having a specular surface for reflection of light into the pores for taking measurements of a fluid isolated therein from the atmosphere.

[0014] In this example, the pores are from 80 to about 100 nm in diameter and from 250 nm to about 1000 nm deep, more particularly about 750 nm, and hold a quantity of fluid when the optically reflective thin layer is immersed in the fluid. The fluid can be selected from ferricyanide, sodium sulfate, water, a gas, or combinations of these. More particularly, the fluid can be a solution of 0.01M ferricyanide, 0.05M sodium sulfate, and deionized water.

[0015] Also in this aspect, the gold film will reflect light transmitted from a direction of the base substrate into the quantity of fluid in the pores when a potential is applied. The quantity of fluid is monitorable by specular reflectance spectroscopy using the reflected light, or by spectroelectrochemical analysis or interferometric analysis or combinations of these methodologies. A detector arranged at about 90° to the reflected light is provided for monitoring and taking measurements.

[0016] In yet another embodiment of the present invention, a thin layer electrode includes a transparent base substrate with a porous thin film

disposed on the base substrate, and a material disposed on the thin film such that the pores are exposed to atmosphere containing a fluid.

[0017] In an aspect of this embodiment, the material is a gold film, which will isolate a portion of the fluid in the pores away from a remainder of the fluid in the atmosphere when a potential is applied. The gold film is also optically reflective when the potential is applied to redirect an incident light beam into the pores as the light beam passes through the transparent base substrate into the pores in a direction of the gold film. Additionally, the gold film has a nanostructured face disposed away from the thin film, which filters scatter-causing particles suspended in the fluid.

[0018] Similar to the foregoing aspects of the invention, the transparent base substrate can be glass and the thin film can be alumina. By way of example, the thin film alumina has a depth of 250 nm to about 1000 nm and exhibits pores of about 80 nm to about 100 nm in diameter and from 250 nm to about 1000 nm deep. Also, the fluid in this aspect is a solution of ferricyanide, sodium sulfate, and water, more particularly deionized water, or a gas, or combinations of these components.

[0019] In another aspect of the invention, a thin layer apparatus for fluid analysis is provided with a transparent base substrate, and a thin film sputtered on the base substrate. The thin film has a plurality of pores, each of which has a diameter of 80 nm to about 100 nm and depths of 250 nm to about 1000 nm. Similar to the foregoing embodiments, the pores isolate a portion of a fluid from a remainder of a bulk fluid in which the thin layer apparatus is immersed.

[0020] A material can be layered on the thin film in this aspect such that the pores remain open in communication with the fluid. The material has a specular surface to reflect into the pores an incident beam entering the pores through the transparent base substrate in a direction of the material such that the isolated fluid in the pores can be analyzed by specular reflectance spectroscopy using the reflected light, or by spectroelectrochemical analysis or interferometric analysis or combinations of these methodologies.

BRIEF DESCRIPTION OF THE DRAWINGS

[0021] The above and other aspects and advantages of the present invention are apparent from the detailed description below in combination with the drawings, in which:

[0022] FIG. 1A is a schematic elevational view of an ORTLE according to an aspect of the present invention;

[0023] FIG. 1B is a SEM image of porous alumina covered with a layer of gold as in FIG. 1A, particularly showing unsealed pores in the porous alumina;

[0024] FIG. 2 is a schematic of a cell in which the ORTLE as in FIG. 1 is mounted;

[0025] FIG. 3 is a schematic plan view of the cell as in FIG. 2;

[0026] FIG. 4 is a graph showing cyclic voltammograms (CV) obtained for a standard gold electrode and the ORTLE as in FIG. 2 immersed in an electrolyte solution with a potential applied;

[0027] FIG. 5 is a graph showing transmission spectra for a glass slide, a glass slide coated with an alumina layer, and the ORTLE as in FIG. 1;

[0028] FIG. 6 is a graph showing specular reflectance spectra including a red shift observed after introduction of a 0.05M sodium sulfate solution and changes in the spectra over time;

[0029] FIG. 7 is a schematic plan view of optical path-lengths of incident light from air through a glass substrate and alumina layer with two reflective interfaces resulting from unanodized aluminum and gold coating;

[0030] FIG. 8 is a graph showing a CV obtained for an ORTLE according to another aspect of the invention;

[0031] FIG. 9a is a graph showing an effect of potential on a specular reflectance spectrum concentrating on a peak at approximately 755 nm; and

[0032] FIG. 9B shows a decrease in magnitude of the reflectance at 780 nm with increasing negative potential, particularly showing by dashed line a dry state of the ORTLE at 780 nm according to another aspect of the invention.

DETAILED DESCRIPTION OF THE INVENTION

[0033] Detailed reference will now be made to the drawings in which examples embodying the present invention are shown. The detailed description uses numerical and letter designations to refer to features of the drawings. Like or similar designations of the drawings and description have been used to refer to like or similar parts of the invention.

[0034] The drawings and detailed description provide a full and detailed written description of the invention and of the manner and process of making and using it, so as to enable one skilled in the pertinent art to make and use it, as well as the best mode of carrying out the invention. However, the examples set forth in the drawings and detailed description are provided by way of explanation of the invention and are not meant as limitations of the invention. The present invention thus includes any modifications and variations of the following examples as come within the scope of the appended claims and their equivalents.

ORTLE Design and Concept

[0035] An optically reflective thin layer electrode (ORTLE) generally designated by the reference numeral 10 is broadly depicted in FIG. 1A. In this example, a 500 nm aluminum film was sputtered substantially onto a base substrate such as a transparent float glass slide 12, anodized and subsequently converted to porous alumina 14. Specifically, a 750 nm-thick, transparent, alumina film 14 results due to conversion from aluminum metal to alumina (aluminum oxide). The alumina film 14 was subsequently coated for 210 seconds with gold using a sputtering system (not shown) such as a CRC-100 sputtering system available from Plasma Sciences Inc. of Lorton, Virginia. The sputtering system produced a gold film 16 approximately 100 nm thick.

[0036] Although the film 16 appears in FIG. 1A to be an optically thick gold film, scanning electron microscopy (SEM) laboratory studies have shown it insufficient to seal the relatively larger pores of a porous alumina membrane. Specifically, a SEM image in FIG. 1B shows that channels or pores 18 of the alumina film 14 created by the above conversion process also remain open when coated with gold in the foregoing manner.

[0037] The gold film 16 possesses a mirror finish on its face 16a - the exposed side opposite the porous alumina 14. Despite this and the apparent continuity of the film 16, it is highly porous thus exposing the channels 18 in the underlying alumina 14 to atmosphere. A reverse side 16b of the gold film 16, however, does not show a highly reflective finish, although it presents a mostly specular surface. As briefly introduced, other metals or materials exhibiting reflective qualities can be substituted for the exemplary gold film 16.

[0038] When exposed to a bulk solution S (see FIG. 2), the channels 18 are filled with a quantity or portion of the solution S. Light can pass through the optically transparent glass slide 12 used as a support and through the fluid-filled alumina 14, but is reflected by the porous metal overlayer 16. If a potential is applied to the gold film 16, any solution S changes that occur within the pores 18 can be monitored by specular reflectance spectroscopy. The ORTLE design advantageously requires no special auxiliary or reference electrodes and no special electrode configurations.

[0039] Those skilled in the art will immediately recognize and appreciate that deeper pores, e.g., greater than about 750 nm, will provide a stronger spectrum of the material in the pores 18, but will take longer to equilibrate with material outside the pores 18 since spectrum strength increases linearly with length. Conversely, shallower pores, e.g., less than about 750 nm, will equilibrate faster for faster measurements but will provide a weaker spectrum since equilibration time increases as the square of length.

Cell Design and Set-Up

[0040] The present cell design is used as a window into the bulk solution S, since only the solution S in the alumina pores 18 is interrogated. As shown in FIG. 2, the ORTLE 10 is mounted in an exemplary cell 20. The cell 20 is constructed from a Teflon[®]-brand material and contained in a rectangular window 22 (e.g., 75 x 75 x 0.5mm) to which the thin layer electrode 10 is attached. The ORTLE 10 is positioned with the gold sputtered surface or side 16 facing inwards as shown and held in place, for instance, by eight screws 24a-h, which can be tightened to avoid leaking of the solution S.

[0041] As described by example operation below, the ORTLE 10 can be used in the foregoing arrangement as a working electrode in the cell 20 for spectroelectrochemical analysis. However, the skilled artisan will recognize that the ORTLE 10 need not be used an electrode nor is the arrangement limited to spectroelectrochemical analysis. For instance, the ORTLE 10 can be used for spectroscopic and interferometric analyses of material trapped in the pores 18 of the alumina 14. As presented below, while an interference pattern can shift to indicate a change in a refractive index of the material filling the pores 18, one skilled in the art can also perform infrared or UV-visible spectroscopy measurements for identification of the pore fluids. Thus, the measurements may not be purely interferometric in nature and may include absorption properties of the fluid.

[0042] With reference to FIGS. 2 and 3, the cell 20 is mounted on an aluminum base 27, which is placed inside a spectrometer 26. The height of this aluminum base 27 is selected to place the ORTLE 10 in a path of an incident light beam L_I emanating from a light source L_S . With the ORTLE 10 so attached, the cell 20 is filled with the desired solution S, into which an auxiliary electrode 28 and a reference electrode 30 are inserted. In this example, the auxiliary electrode 28 is platinum (Pt) gauze and the reference electrode 30 is Ag/AgCl/sat: NaCl, available from BAS of West LaFayette, Indiana. Also by way of example, an OL 750-75MA Automated Goniospectroreflectance Attachment, available from Optronic Laboratories, Inc. in Orlando, Florida, is suitable for use as the spectrometer 26.

[0043] As shown in FIG. 3, the cell 20 is illuminated by the light source L_S , such as a tungsten quartz-halogen lamp (150 W) and a 750 M-S Monochromator combination. This light source combination L_S has selectable wavelengths in the range of 280-1100 nm. The Monochromator in this example is available from Optronic Laboratories, Inc, but may be substituted with other suitable devices.

[0044] A silicon detector 32 in FIG. 3 is used to record intensity of reflected light L_R . An exemplary detector is available from Optronic Laboratories, Inc. under the designation "DH-300EC, OL750-HSD-301EC". Spectra (see, e.g., FIG. 6) are obtained by appropriate software such as that available from Optronic Laboratories, Inc. The spectra are analyzed using, for

example, IGOR Pro, Version 4.01, available from Wavemetrics, Inc. of Lake Oswego, Oregon.

[0045] All electrochemical experiments in the examples detailed below are carried out using an EG&G PARC Model 263 potentiostat connected with a general purpose interface bus (GPIB), available from National Instruments of Atlanta, Georgia. The GPIB is connected to a Gateway 2000 Model P5-60 computer with EG&G Model 270 Research Electrochemistry Powersuite Software. Gold wire electrodes are available from CH Instruments of Austin, Texas. Potassium ferricyanide is available from Mallinckrodt of Hazelwood, Missouri, and sodium sulfate is available from Fisher Scientific of Suwanee, Georgia. The potassium ferricyanide and sodium sulfate are all reagent grade and are used without further purification. All solutions were prepared with deionized water. SEM images were collected using a Quanta 200 scanning electron microscope available from FEI Company of Hillsboro, Oregon.

[0046] Those skilled in the art will recognize that the foregoing equipment and materials are provided by way of example only and many suitable substitutions can be made to practice the invention as described below.

[0047] The present invention may be better understood with respect to the following examples.

EXAMPLES

[0048] With reference to the figures and for exemplary purposes only, the following methodologies and embodiments are employed for interrogation of a solution phase within pores of the film in the ORTLE 10.

Example 1 - Characterization of the ORTLE

[0049] FIG. 4 depicts results of the ORTLE 10 used as a working electrode. As shown, a comparison is made between a cyclic voltammogram (CV) obtained at a conventional gold wire electrode (A) and one obtained using the ORTLE 10 as a working electrode (B). Both experiments were carried out in 0.01 M ferricyanide/0.05M sodium sulfate solutions at 20mVs⁻¹. According to FIG. 4, the ORTLE 10 behaves similarly to the wire electrode (A). The purely electrochemical characteristics of the ORTLE electrode reflect those of bulk solution conditions because the electrode 10 is immersed

in bulk solution. This experiment shows the ability of the ORTLE 10 to exhibit the standard characteristics that would be expected in a ferricyanide solution given that the design of the electrode 10 is such that the very thin gold layer 16 sputtered on the porous alumina film 14 does not seal the pores 18 as previously described.

[0050] More specifically, FIG. 4 shows a decrease in the separation of the peaks for the ORTLE 10, which would be expected for a contribution from restricted diffusion occurring within the pores 18. To test this, an experiment was conducted to measure the effect of sweep rate (v) on the peak current. For a thin layer cell, the peak current should be directly proportional to v . This experiment revealed a poor relationship between peak current and v and an excellent relationship between peak current and $v^{1/2}$ ($R^2 = 0.999$). The result indicates that for this CV the contribution of thin layer electrochemistry is negligible compared to that of the bulk solution.

[0051] Turning to FIG. 5, a plot shows transmitting spectra of a plain float glass microscope slide (A), of a similar glass slide with a layer of porous alumina (B), and of an ORTLE (C), all taken at an angle θ , e.g., about 45°, to an incident beam (see, e.g., L_1 in FIG. 3). Interference effects in the spectrum (B) are the result of the refractive index contrast between glass and the overlying films, while the reduced overall transmittance of the ORTLE is negligible on the scale of FIG. 5 due to the presence of the reflective gold film and thus little interrogation of the bulk solution can occur through the film. Spectroscopic changes based on specular reflectance on the backside of the gold film must therefore be ascribed to either changes in the medium within the pores or changes in the electrode itself.

[0052] FIG. 6 shows a typical specular reflectance spectrum (solid black line) obtained for the ORTLE 10 without any solution in the cell (see, e.g., cell 20 in FIG. 2). The specular reflectance measurements were performed by positioning the cell at angle θ , e.g., about 25° to 75°, more particularly 45°, to the incident beam L_1 , and the detector 32 at about 80° to 95°, more particularly 90°, to the specular reflected beam (see FIG. 3). By positioning the cell 20 and the detector 32 at relatively steeper angles, pathlength and sensitivity of the reflected beam are increased. Further, steeper angles introduce polarization effects that can be used for internal calibration of the components.

[0053] With continued reference to FIG. 6, single-beam reflectance measurements were referenced to the total intensity of the source by directing 100% of the incident beam to the detector before each experiment. Several small interference peaks can be observed at shorter wavelengths with a relatively large peak usually observed within the range of approximately 700-1000 nm (the wavelengths and the appearance of the peaks varied from ORTLE to ORTLE due to slight differences in the thickness of the original aluminum films). Upon the introduction of a sodium sulfate solution, the peaks shifted towards longer wavelengths, accompanied by an increase in intensity – for this sample the large peak shifted from 850 to 900 nm, as indicated by the spectrum collected after 0 min (i.e., it was collected immediately after the introduction of the sodium sulfate solution). The spectra collected after 60 min and 120 min show that for this ORTLE no further red shifts or increases in intensity were observed. While this particular ORTLE responded promptly, some ORTLEs showed a gradual red shift over time after solution was introduced. In all cases, less than 1 hour was necessary for this change to be completed. At least part of this change is likely the result of pores being filled with solution and changing the effective refractive index of the porous film, as the shift is consistent with changes in interference fringe positions expected in that case within a factor of two.

[0054] Referring now to FIG. 7, one condition for the appearance of strong interference-based oscillations in the reflection spectrum of the ORTLE 10 is that the reflectivity of a glass/alumina interface 15 and an alumina/gold interface 17 are of comparable magnitudes. This is achieved only because the electrochemical synthesis of the porous alumina film 14 leaves a small amount of aluminum metal behind at the glass/alumina interface 15, approximately 1.2 nm thickness on average as indicated by ellipsometry. Aluminum is the most opaque metal in the visible region. According to optical modeling of this electrode, too much aluminum at the interfaces 15,17 (e.g., 50 nm) would cause the spectrum of the ORTLE 10 to be that of an aluminum mirror. Too little aluminum at the interfaces 15, 17 would produce a spectrum like that of a gold mirror with small (e.g., 5%) interference oscillations in the blue and ultraviolet, dropping to about 1% oscillation in the red and near infrared.

[0055] With this first condition met, constructive interference in reflection occurs when the difference in the optical pathlengths a and b are an integral number of wavelengths of incident light. Assuming an isotropic material with no absorbance, the optical pathlength is the physical pathlength multiplied by the (real) refractive index of the medium. Making use of Snell's law:

$$\sin(\theta_0) = n_1 \sin(\theta_1) = n_2 \sin(\theta_2)$$

where θ_0 is the angle of the incident light L_i from air to the glass substrate 12, θ_1 is the angle that the beam enters the porous alumina layer 14 from the glass substrate 12, θ_2 is the angle of the beam that interacts with the gold layer 16 and n_1 and n_2 are refractive indices of the glass 12 and porous alumina layer 14, respectively.

[0056] It is possible to show that the optical path difference (OPD) is:

$$OPD = 2d\sqrt{n_2^2 - \sin^2(\theta_0)} = m\lambda_{\max}$$

, where m is a non-negative integer, d is the film thickness and λ_{\max} is the maximum wavelength. The apparent refractive index of the film, n_2 , is approximately related to the volumetric composition of the films, assuming the film structure to be heterogeneous on a scale less than the wavelength of light and with no regular repeating patterns.

[0057] For the dry film,

$$n_2 \approx n_{Al_2O_3} (1 - f_p) + f_p$$

where $n_{Al_2O_3}$ is the refractive index of alumina, f_p is the pore fraction of the porous alumina and the refractive index of air is taken to be 1. As the pores of the alumina film fill with solution Equation 3 becomes:

$$n_2 \approx n_{Al_2O_3} (1 - f_p) + 1.33 f_p$$

where the refractive index of the filling solution is assumed to be that of water.

For any value of m ,

$$\frac{\lambda_{\max,dry}}{\lambda_{\max,wet}} = \frac{\sqrt{n_{2,dry}^2 - \sin^2(\theta_0)}}{\sqrt{n_{2,wet}^2 - \sin^2(\theta_0)}}$$

Since the refractive index of the solution filled film is always greater than that of the dry film, the filling of the pores will always result in a red shift.

Example 2 - Reduction of Water

[0058] In a further aspect of the invention, experiments by specular reflectance spectroscopy on the ORTLE as a function of potential in a simple solution of 0.05 M Na₂ SO₄ provided the following results. The exemplary embodiment described below is similar to the foregoing embodiment; therefore, those skilled in the art will refer to the previous embodiment for enabling descriptions of similar components, construction and operation of the ORTLE.

[0059] For these experiments, the auxiliary and reference electrodes 28, 30 as shown in FIG. 2 were inserted into the cell 20 and the three electrodes 10, 28, 30 were connected to the potentiostat (not shown). FIG. 8 shows a CV of the Na₂ SO₄ solution where the potential was swept from +0.4V to -1.5V vs. (Ag/AgCl). The positive potential limit observed for the ORTLE 10 was apparently due to the gold oxide formation. More positive potentials resulted in delamination of the fragile gold film 16 from the porous alumina substrate 14, a common indicator of stress at a film/substrate interface 34. The negative potential limit of the ORTLE 10 was not due to delamination but apparently to dissolution of the porous alumina 14 by hydroxide ions generated during hydrogen evolution. The cathodic current associated with hydrogen evolution can be seen to begin at approximately -1.1V (vs. Ag/AgCl) in FIG. 8.

[0060] An ORTLE 10 for which results are depicted in FIG. 9A show a "dry" reflectance spectrum in which one of the observed peaks was centered at 725 nm. The addition of the sodium sulfate solution to the cell 20 caused this peak to shift to 755 nm. Reflectance spectra were acquired during the 400s that the potential was held at a certain value for steps to potentials between +0.1V and -1.2V (vs. Ag/AgCl). FIG. 9A shows detail in the reflectance spectrum of the ORTLE 10 at a subset of these potentials, between -0.4V and -1.1V (vs. Ag/AgCl), with the "dry" spectrum for reference.

[0061] No significant changes were observed in the ORTLE reflectance spectra at potentials positive of -0.5V (vs. Ag/AgCl). When the potential was stepped to -0.5V (vs. Ag/AgCl), however, a blue shift of the peaks was observed. As FIG. 9A shows, the interference peak at 755 nm continued to shift toward the blue very gradually with increasing negative potential until -1.0V. A decrease in intensity was not observed over this potential range; in

fact, a slight increase in intensity was observed. When the potential was stepped to -1.1V , however, a more pronounced blue shift of the large peak at 755 nm was observed that was accompanied by a substantial decrease in intensity. This is interpreted as a result of gas infiltrating the pores of the alumina. Spectra obtained at more negative potentials showed weaker and broader interference peaks that did not recover when the electrode was returned to more positive potentials. This is interpreted as a result of the concomitant generation of hydroxide during hydrogen evolution. It is possible that the pH may be controlled with a buffer solution.

[0062] In electrochemical experiments carried out with ORTLEs outside of the spectrometer, it was not possible to see hydrogen evolution with the naked eye until the potential approached -1.5V . The increase in current observed in FIG. 8 near -1.1V is, however, attributable to the onset of water reduction. The low level of hydrogen production occurring at -1.1V was insufficient to form bubbles large enough to be observed by the naked eye, but sufficient to strongly perturb the ORTLE specular reflectance. Assuming pores to be filled initially with water and that this water is displaced by gaseous hydrogen generated at the electrode, the apparent refractive index of the film can be written as:

$$n_2 \approx n_{\text{Al}_2\text{O}_3} (1 - f_p) + 1.33 f_p - \frac{RT n_{\text{H}_2}}{3dA}$$

where n_{H_2} is the number of moles of H_2 produced, A is the area of the electrode, R is the ideal gas constant, and T is the absolute temperature.

[0063] Inserting this definition into equation 2, solving for wavelength and taking the derivative with respect to the number of moles of H_2 produced under initial conditions of pores filled with only water or a water-like electrolyte, the following is obtained:

$$\lambda_{\max} = \frac{2d\sqrt{(n_{Al_2O_3} - f_p(n_{Al_2O_3}, -1.33))^2 - \sin^2(\theta_0)}}{m}$$

$$\frac{\partial \lambda_{\max}}{\partial n_{H_2}} = \frac{2RT(n_{Al_2O_3} - f_p(n_{Al_2O_3}, -1.33))}{3mA\sqrt{(n_{Al_2O_3} - f_p(n_{Al_2O_3}, -1.33))^2 - \sin^2(\theta_0)}}$$

[0064] Inserting a void fraction of 0.32 (estimated from ellipsometry), a film thickness d of 680 nm (estimated from modeling of the film in FIG. 6), and an incident angle of 45 degrees, the maxima should occur at:

$$\lambda_{\max} \approx \frac{1851\text{nm}}{m}$$

[0065] From Equation 5, it is evident that $m = 2$ for the long wavelength peak in FIG. 6, and m is 3, 4 and 5 for the peaks at progressively shorter wavelengths. Returning to Equation 4, the sensitivity of the peak position of the $m = 2$ peak to hydrogen is:

$$\frac{\partial \lambda_{\max}}{\partial n_{H_2}} = \frac{9 \times 10^{10} \text{nm} \cdot \text{mol}^{-1} \cdot \text{cm}^2}{A}$$

[0066] Equation 6 indicates that 0.1 nanomole of H_2 produced per centimeter squared area of electrode surface could result in a 9 nanometer hypsochromic shift in the $m = 2$ peak. Assuming that a 1 nm shift could be detected, and assuming the sensor on the end of a fiber-optic with an area of 10^{-4} cm, approximately 1fM of H_2 evolution could be detected if the gas were captured in the pores of the alumina.

[0067] Subtle shifts in the wavelength of the interference peak maximum in FIG. 9A were observed at potentials as positive as -0.5V (vs. Ag/AgCl). The origin of this shift is unknown at present, but must involve changes in the composition of the porous film or of the solution in the pore volume. The blue shift indicates an overall decrease in the optical thickness of the film under these conditions, an effect that is consistent with displacement of pore solution by nanoscale bubbles. In FIG. 9B, the variation in the magnitude of the reflectance at 780 nm is plotted against potential. As shown, the intensity follows a similar trend with varying potential, in that a large increase of intensity is observed upon the addition of solution and a gradual decrease observed with increasing negative potential. Eventually, at -1.1V, FIG. 9B shows that the intensity is similar to that of the electrode in the dry state.

Conclusion

[0068] A thin layer film based on a gold-coated, porous alumina film, for example, has been shown and described. The thin layer film was placed in a cell and subjected to cyclic voltammetry and spectroscopic techniques and by spectroelectrochemistry in which a combination of specular reflectance spectroscopy and chronoamperometry was used. Typical spectra exhibited several strong interference peaks that resulted from the presence of a small amount of unanodized aluminum at the glass/porous alumina interface. A red shift of the peaks in the specular reflectance spectrum and an increase in intensity was observed upon the introduction of a sodium sulfate solution to the spectroelectrochemical cell where the ORTLE was mounted. This is likely due to refractive index changes arising from the filling of the pores by the solution. A blue shift of the peaks could be induced by stepping the potential to values increasingly negative of -0.5V (vs. Ag/AgCl) and towards the background limit of the solution. Upon stepping to -1.1V, a pronounced blue shift was observed, accompanied by a decrease in intensity. This is likely due to the production of hydrogen within the pores of the ORTLE.

[0069] The ORTLE differs from typical thin-layer electrodes in several ways. First, no transparent electrodes are required, and the solution does not have to be transparent or even homogenous, because the nanostructured electrode face filters out particles large enough to cause significant scattering. The electrode can thus be used in bulk solutions as a window that does not allow light into the bulk – similar to total internal reflection techniques, but with no critical angle constraints. Further, the electrode can potentially be designed to combine refractive-index measurements with surface plasmon resonance and UV-visible absorbance measurements with very minor changes. Moreover, while a top layer of the ORTLE can be a metal, the top layer is not limited to use as an electrode for spectroelectrochemical analysis. Additionally, while the interference pattern shifts described above indicate a change in the refractive index of the material filling the pores, measurements are not limited to interferometry but can include absorption properties of the fluid. Thus, one can also use the ORTLE to perform infrared or UV-visible spectroscopy measurements on the fluids in the pores to identify those fluids.

[0070] While preferred embodiments of the invention have been shown and described, those skilled in the art will recognize that other changes and modifications may be made to the foregoing examples without departing from the scope and spirit of the invention. It is intended to claim all such changes and modifications as fall within the scope of the appended claims and their equivalents. Moreover, references herein to "top," "bottom," "upward," "upper," "higher," "lower," "downward," "descending," "ascending," "side," "first," and "second" structures, elements, designations, geometries and the like are intended solely for purposes of providing an enabling disclosure and in no way suggest limitations regarding the operative orientation or order of the exemplary embodiments or any components thereof.